T.C

(MASTER THESIS)

YAŞAR UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCE

TEMPERATURE MEASUREMENT AND CONTROL CIRCUIT

Habibu Aminu HUSSAIN

Thesis Advisor: Prof. Dr. Coşkun İŞÇİ

Department of Electrical and Electronics Engineering

Bornova -İzmir

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APPROVAL PAGE

This study titled "TEMPERATURE MEASUREMENT AND CONTROL CIRCUIT" and presented as MSc Thesis by Habibu Aminu HUSSAIN has been evaluated in compliance with the relevant provision of Y.U Graduate Education and Training Regulations of Y.U institute of Science Education and Training Directions. The jury members below have decided for the defense of this thesis, and it has been declared by consensus/ majority of votes that the candidate has succeeded in his thesis defense. Examination dated 23rd May, 2014.

Jury Members:	**Signature:**
Head: ……………………..	………………………
Rapporteur Member: ……………………..	……………………….
Member: ……………………..	………..…………….

TEXT OF OATH

I declare and honestly confirm that my study titled "TEMPERATURE MEASUREMENT AND CONTROL CIRCUIT", and presented as Master's Thesis has been written without applying to any assistance inconsistent with scientific ethics and traditions, that all sources from which I have benefited listed in bibliography, and that I have benefited from these sources by means of making references.

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ÖZET

SICAKLIK ÖLÇME VE KONTROL

Habibu Aminu HUSSAIN

MSc in Electrical and Electronics Engineering

Supervisor: Prof. Dr. Coşkun İŞÇİ

May 2014

Mühendislik ve endüstride ki birçok olay sıcaklığa bağlıdır. Bu nedenle, farklı sıcaklık ölçme, kayıt ve control sistemleri oldukça önemlidir. Bu araştırmanın amacı, farklı sıcaklık algılama sensörleri ile sıcaklığı ölçme, control etme ve sensörlerin Mathematica paket programı ile kalibrasyonu yöntemlerini , incelemek ve uygulamaktır. Termoçift, thermistor, bimetalik termometre, klasik termometre, LM35 entegre devre ve infrared thermometer ile ölçümler yapılmış ve sonuçlar kıyaslanmıştır. Ultrasonik ve priometre ile sıcaklık ölçümleri de araştırılmıştır. Termoçiftin uçlarında oluşan emk, digital voltmeter ile sıcaklığın fonksiyonu olarak ölçülmüştür. Mikro volt düzeyindeki voltaj değerleri LM308 opamp ile 1000 kez yükseltildikten sonra, referens voltajı ile kıyaslanmak üzere LM358 differential opamp a gönderilmiştir. Bu kıyaslama control devresi, bir translator ile elektromekanik röle devresini ON/OFF yaparak ısıtıcıyı çalıştırmıştır. Alumel-Kromel ince tellerden yapılmış termoçiftin uçlarındaki elektromotor kuvvet (emk), üç belirli sıcaklıkta ölçülerek kalibrasyona gidilmiştir. Bunun için termoçift ile ilgili kübik denklemin katsayıları, Mathematica-9 computer programı ile hesaplanmış ve sonra gerekli çizelge oluşturulmuş ve grafikler çizilmiştir.

ABSTRACT

TEMPERATURE MEASUREMENT AND CONTROL CIRCUIT

Habibu Aminu HUSSAIN

MSc in Electrical and Electronics Engineering

Supervisor: Prof. Dr. Coşkun İŞÇİ

May 2014

In engineering and industry, many events depend on the temperature. Therefore different methods of temperature measurement recording and control are very important. The aim of this research is to study different temperature measurement techniques, with the help of some sensors and computer program to create a calibration and electronic temperature control system. Some of the temperature measurement techniques that were studied include: Thermocouple, Thermistors, Pyrometer, Bimetallic thermometer, LM35, Infrared and Ultrasonic measurement. The electromotive force (potential difference, emf) between the ends of a thermocouple is too small to measure by some analog devices. Some sensitive digital devices can be used for direct measurements. By means of a simple amplifier circuit (LM308), emf of a few micro volts was amplified to 1000 times in order to increase it to a measurable level. LM358 op amp was used as a comparator to compare the amplified signal against the reference voltage. Then a transistor was also used, which can switch other equipment ON and OFF or toggle a relay. A thermocouple made of alumel and chromel alloys thin wire was calibrated by measuring three voltages at three different temperatures. The emf on a thermocouple is a cubic equation in terms of temperature. This cubic expression is then solved by a computer program written in Mathematica.

Keywords: Sensor, calibration, Comparator

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TABLE OF CONTENTS

Page

APPROVAL PAGE iii
TEXT OF OATH iv
ÖZET v
ABSTRACT vi
ACKNOWLEDGMENTS vii
TABLE OF CONTENTS viii
INDEX OF FIGURES xi
INDEX OF TABLES xiii
CHAPTER ONE 1
INTRODUCTION 1
1.1 Heat 1
1.2 Heat Transfer 1
1.3 Temperature 2
1.4 Temperature Measurement and Control 2
CHAPTER TWO 4
TEMPERATURE MEASUREMENT TECHNIQUES 4
2.1 THERMOMETERS 4
2.1.1 Mercury in Glass Thermometer 4
2.1.2 Alcohol Thermometer 6
1.1.3 Bimetallic Thermometer 7
2.2 TEMPERATURE SENSORS 8
2.2.1 Thermocouple 8

TABLE OF CONTENTS (Cont'd)

Pages

2.2.2 Thermistor 10

2.2.3 LM35, LM135, LM235 AND LM335 IC Sensors 10

2.2.4 Resistance Thermometer 11

2.3 OPTICAL TECHNIQUES 11

2.3.1 Pyrometer 12

2.3.2 Infrared Thermometer 12

2.4 ULTRASONIC TEMPERATURE MEASUREMENT 13

CHAPTER THREE 15

THERMOCOUPLE AND THERMISTORS 15

3.1 PRINCIPLE OF THERMOCOUPLE 15

3.2 Type of Thermocouples 15

3.3 Thermocouple Calibration Mathematica Program 16

3.3.1 Matrix Method 19

3.3.2 Curve Fitting 21

3.4 LM35 CALIBRATIONS 21

3.5 THERMISTOR MEASUREMENT 23

CHAPTER FOUR 26

CONTROL CIRCUIT 26

4.1 OPERATIONAL AMPLIFIER AND DIFFERENTIAL AMPLIFIERS 26

4.1.1 LM308 26

4.1.2 LM358 27

4.2 RELAY AND TRANSISTOR 28

4.2.1 Relay 28

TABLEOF CONTENT (Cont'd)

Pages

4.2.2 Transistor........28
4.3THERMOCOUPLE CONTROL CIRCUIT........29
4.4 HEATING AND CONTROL........30
4.5. MEASUREMENT AND CONTROL USING THERMISTOR........31
4.6 LM135, LM235 AND LM335 CIRCUITS........31
4.7 THERMOCOUPLE CALIBRATION........32
4.7.1 Matrix Method........33
4.7.2 Curve Fitting........34
CHAPTER FIVE........36
5.1 SUMMARY........36
5.2 CONCLUSION........37
5.3 SUGGESTIONS........38
5.4 APPENDICES…………………………………… ……………….39
5.5 BIBLIOGRAPHY........44

INDEX OF FIGURES

FIGURE Page

1 Operational amplifier 3
2 Mercury in Glass Thermometer 5
3 (a) Maximum Thermometer / (b) Clinical Thermometer 6
4 Alcohol Thermometer with Red Dye Inside 7
5 Bimetallic Thermometer 8
6 How Thermocouple Works 9
7 How Thermocouple Works 9
8 Thermocouple Measurement 17
9 Thermocouple Calibration 17
10 Graph of Potential Difference against Temperature for Thermocouple 19
11 Graph of Potential Difference against Temperature for LM35 22
12 The Photograph of LM35 Calibrations Circuit 23
13 Graph of Potential Difference against Temperature for Thermistor 25
14 Photograph of the Constructed Circuit for the Calibration of Thermocouple Thermistor and LM35 25
15 Pin Configuration of LM308 Op-amp 26
16 LM308 Amplification Circuit 27
17 LM358 Comparator Circuit 28
18 12V DC relay 28
19 Transistor Symbol 29
20 Thermocouple Based Control Circuit 29
21 Thermocouple Control Circuit 30
22 Circuit Diagram of a Temperature Control Using Thermistor 31
23 Circuit Diagram of a Temperature Control Using LM35 32
24 Thermocouple Measurement 33
25 Graph Plot by Mathematica of Temperature and Potential Difference Relationship for Themocouple 35

INDEX OF FIGURES (Cont'd)

FIGURE Page

26 Graph Plot by Mathematica of Temperature and Potential Difference Relationship for Themocouple 35

27 Graph Plot by Mathematica of Temperature and Potential Difference Relationship for Thermocouple 35

INDEX OF TABLES

TABLE | Page

1 Temperature and Voltage Relationship of a Thermocouple 18

2 Temperature and Voltage Relationship of LM35 Temperature Sensors 22

3 Temperature and Resistance Relationship of a Thermistor 24

CHAPTER ONE

INTRODUCTION

1.1 Heat

Heat energy is the result of the movement of very small particles called atoms, molecules or ions in solids, liquids and gases. Heat energy can be transferred from one object to another and the transfer or flow due to the difference in temperature between the two objects is called heat. All matter is made of very small particles called atoms, molecules and ions. These small particles are always in constant random movement either colliding into each other or vibrating to and pro. It is the movement of these particles that creates a form of energy called heat (or thermal) energy that is present in all matter.

1.2 Heat Transfer

Heat transfer is a discipline of thermal engineering that concerns the generation, use, conversion, and exchange of thermal energy and heat between physical systems. Heat transfer is classified into various mechanisms, such as thermal conduction, thermal convection and thermal radiation.

1.2.1 Conduction

When an object is heated, its' particles gain energy and vibrate more rapidly. The particles collide with nearby particles and make them vibrate more. The particles pass the thermal energy through the object by conduction, from the hot to the cold end. In metals, free electrons are responsible for heat conduction.

1.2.2 Convection

When particles in liquids and gases get heated, they become lighter, and they rise. The space they left is quickly replaced by cooler particles that are less dense (because they are heavier). That’s how thermal energy is transferred from hot places to cold places (air or liquid) by convection.

1.2.3 Radiation

All objects transfer thermal energy by emitting infra-red radiation. The hotter an object is, the more infra-red radiation it gives off. No particles are involved in radiation, unlike conduction and convection. This means that thermal energy transfer by radiation can even work in space, but conduction and convection cannot.

1.3 Temperature

Temperature is the degree or intensity of heat present in a substance or object, especially as expressed according to a comparative scale and shown by a thermometer or perceived by touch.

A temperature is a numerical measure of hot or cold. Its measurement is by detection of heat radiation or particle speed or kinetic energy. It may be calibrated in any of various temperature scales, Celsius, Fahrenheit, Kelvin, etc. The fundamental physical definition of temperature is provided by thermodynamics.

Measurements with a small thermometer, or by detection of heat radiation, can show that the temperature of a body of material can vary from time to time and from place to place within it. For example, a lightning bolt can heat a small portion of the atmosphere hotter than the surface of the sun. If changes happen too fast, or with too small a spacing, within a body, it may be impossible to define its temperature [1].

1.4 Temperature Measurement and Control

Many devices have been invented to accurately measure temperature. It all started with the establishment of a temperature scale. This scale transformed the measurement of temperature into meaningful numbers.

In the early years of the eighteenth century, Gabriel Fahrenheit (1686-1736) created the Fahrenheit scale. He set the freezing point of water at 32 degrees and the boiling point at 212 degrees. These two points formed the anchors for his scale [2].

Later in that century, around 1743, Anders Celsius (1701-1744) invented the Celsius scale. Using the same anchor points, he determined the freezing temperature for water to be 0 degree and the boiling temperature 100 degrees. The Celsius scale is known as a Universal System Unit. It is used throughout science and in most countries [2].

1.4.1 Temperature Control

Temperature control is a process in which change of temperature of a space (and objects collectively there within) is measured or otherwise detected, and the passage of heat energy into or out of the space is adjusted to achieve a desired average temperature.

With the help of some amplification circuit like op-amp and switching circuits, temperature of certain equipment can be controlled.

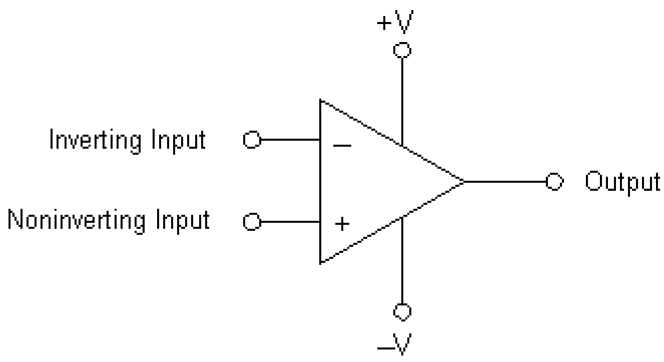

Figure 1: Operational amplifier

CHAPTER TWO

TEMPERATURE MEASUREMENT TECHNIQUES

2.1 THERMOMETERS

A thermometer is a device that measures temperature or temperature difference using a variety of different principles. A thermometer has many important components: the temperature sensor (e.g. the bulb on a mercury-in-glass thermometer) whereby some physical change happens with respect to temperature, in addition to other ways of converting this physical change into a numerical value (e.g. the visible scale that is marked on a mercury-in-glass thermometer).

Thermometers measure temperature, by using materials that change in some way when they are heated or cooled. In a mercury or alcohol thermometer the liquid expands as it is heated and contracts when it is cooled, so the length of the liquid column is longer or shorter depending on the temperature. Modern thermometers are calibrated in standard temperature units such as Fahrenheit or Celsius.

2.1.1 Mercury in Glass Thermometer

A mercury-in-glass thermometer is a thermometer that provides temperature readings through the expansion and contraction of mercury inside a calibrated tube (usually glass tube). These devices were used to measure temperatures in a different form of settings from the 1700s until the 20th century. These devices have a large bulb filled with mercury at the bottom of the thermometer, attached to a thin tube. As the temperature increase, the mercury expands, moving up the tube. The temperature can be read by locating the mark that corresponds with the height of the mercury. As the temperature decreases, the mercury contracts, shrinking back down into the bulb.

In a very cold temperature, this type of thermometer will not work, because the mercury itself will be frozen. With a maximum thermometer, the mercury will be held at the highest point until the thermometer is shaken, allowing the maximum temperature to be read on the thermometer.

Figure 2: Mercury in Glass Thermometer

In order to calibrate the thermometer, the bulb is made to reach thermal equilibrium with a temperature standard such as an ice/water mixture, and then with another standard such as water/vapor, and the tube is divided into regular intervals between the fixed points. In principle, thermometers made of different material (e.g., colored alcohol thermometers) might be expected to give different intermediate readings due to different expansion properties; in practice the substances used are chosen to have reasonably linear expansion characteristics as a function of true thermodynamic temperature, and so give similar results.

(a) Maximum Thermometer

This customize mercury-in-glass thermometer, works by having a constriction in the neck close to the bulb. As the temperature increases, the mercury is moved up through the constriction due to the force of expansion. When the temperature decreases, the column of mercury breaks at the constriction and cannot return to the bulb, thus staying stationary in the tube. The maximum temperature can then be read over the set period of time. The thermometer must be shack to return it back to its original state.

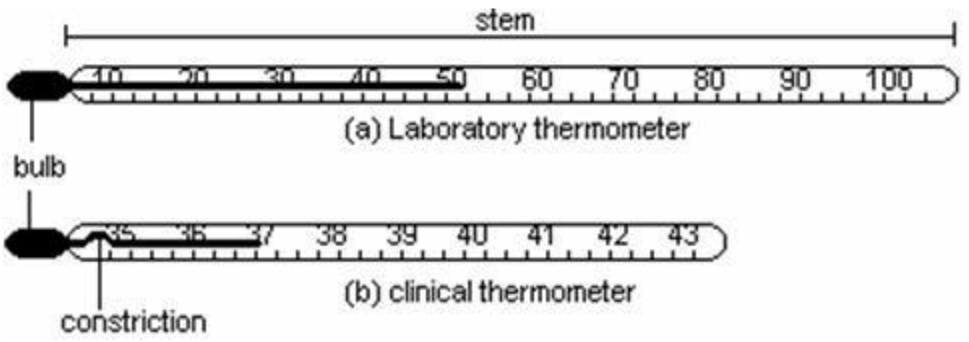

Figure 3: (a) Maximum Thermometer / (b) Clinical Thermometer

(b) Maximum Minimum Thermometer

A maximum minimum thermometer, also known, is a thermometer which registers the maximum and minimum temperatures reached over a period of time, typically 24 hours. The original design contains mercury, but solely as a way to indicate the position of a column of alcohol whose expansion indicates the temperature; it is not a thermometer operated by the expansion of mercury; mercury-free versions are available.

2.1.2 Alcohol Thermometer

The Alcohol thermometer or spirit thermometer is an alternative to the mercury-in-glass thermometer, and operate in the same manner. But unlike mercury-in-glass thermometer, the contents of an alcohol thermometer are less poisonous and will evaporate away quickly. An organic liquid is contained in a glass bulb which is joined to a capillary of the same glass and the end is closed with an expansion bulb. The space above the liquid is a mixture of nitrogen and the vapor of the liquid. For the working temperature range, the interface between the liquid is within the capillary. With increasing temperature, the volume of liquid expands and the meniscus moves up the capillary. The position of the meniscus shows the temperature against an inscribed scale.

The liquid used can be pure ethanol, toluene or kerosene, depending on manufacturer and working temperature range. Since these are transparent, the liquid is made more visible by the addition of a red or blue dye. One half of the glass containing the capillary is usually enameled white or yellow to give a background for reading the scale. The liquid is commonly called Thermo Juice.

The range of usefulness of the thermometer is set by the boiling point of the liquid used. In the case of the ethanol-filled thermometer the upper limit for measurement is 78 °C (172 ºF), which makes it useful for measuring day and night-time temperatures and to measure body temperature, although not for anything much hotter than these. The ethanol version is the most widely used due to the low cost and relatively low hazard posed by the liquid in case of breakage [3].

Figure 4: Alcohol Thermometer with Red Dye Inside

1.1.3 Bimetallic Thermometer

Bimetallic thermometers are made up of bimetallic strips formed by joining two different metals having different thermal expansion coefficients. Basically, bimetallic strip is a mechanical element which can sense temperature and transform that temperature into a mechanical displacement. This mechanical motion from the bimetallic strip can be used to activate a switching mechanism for getting electronic output. It can also be attached to the pointer of a measuring instrument or a position indicator.

The working of a bimetallic strip thermometer is based upon the fact that two different kinds of metals behave in different ways when exposed to temperature changes owing to their different thermal expansion rates. One layer of metal expands or contracts more than the other layer of metal in a bimetallic strip arrangement which leads to bending or curvature change of the strip. One end of a straight bimetallic strip is clamped in place. As the strip is heated, the other end tends to curve away from the side that has the greater coefficient of linear expansion.

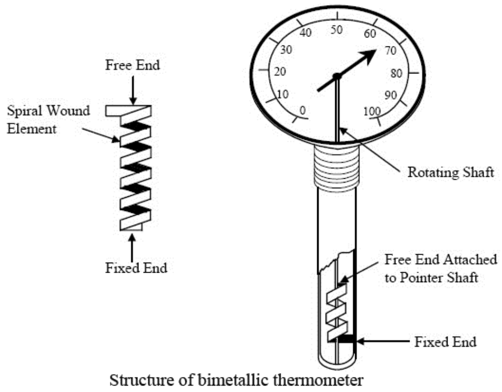

Figure 5: Bimetallic Thermometer

2.2 TEMPERATURE SENSORS

Temperature sensors are very important to different kinds of everyday products. For example, Refrigerators, Heating system, and thermostats all depend on temperature regulation and control in order to work properly.

From a thermodynamics point of view, temperature changes as a function of the average energy of molecular movement. As heat is added to a system, molecular movement increases and this result in an increase in temperature. However, it is hard to directly measure the energy of molecular movement, so temperature sensors are generally designed to measure a property which changes in response to temperature. The devices are then calibrated to traditional temperature scales using a standard (i.e. the boiling point of water at known pressure).

2.2.1 Thermocouple

A thermocouple is a temperature-measuring device consisting of two dissimilar conductors that contact each other at one or more spots. It produces a voltage when the temperature of one of the spots differs from the reference temperature at other parts of the circuit. Thermocouples are a widely used type of temperature sensor for measurement and control and can also convert a temperature gradient into electricity. In contrast to most other methods of temperature measurement, thermocouples are self-powered and require no external form of excitation. Any junction of dissimilar metals will produce an electric potential related to temperature. Thermocouples for practical measurement of temperature are junctions of specific alloys which have a predictable and repeatable relationship between temperature and voltage. Different alloys are used for different temperature ranges.

(a) How Thermocouple Works

The simplest answer to how thermocouples work is when you have two different kinds of wire twisted together as shown below. If temperature T1 is different from T2 then current will flow through the wires. This effect was discovered by T.J. Seebeck in 1831.

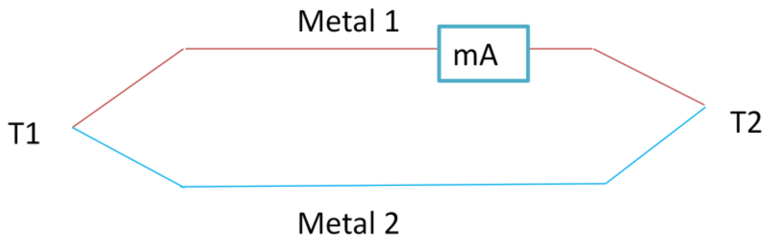

Figure 6: How Thermocouple Works

Seeback also discovered that the voltage potential that was generated was almost directly proportional to the difference in the two temperatures, that is if we connected a multimeter which was capable of measuring very low voltages across the two wires as shown below; then we could multiply the voltage by a constant and get the temperature difference between T1 and T2. This constant is based on the type of metals used for the wires.

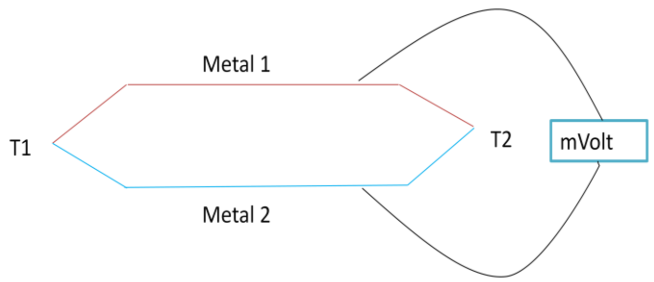

Figure 7: How Thermocouple Works

2.2.2 Thermistor

A thermistor is a type of resistor whose resistance varies significantly with change in temperature. Thermistors are widely used as temperature sensors, over current protectors and self-regulating heating element. Thermistors use internal electrodes that sense surrounding heat and measure it through electrical impulses.

How Thermistor Works

There are 2 types of Thermistors, The PTC and the NTC. The resistance of the PTC (positive thermal coefficient) increases with increasing temperature. The resistance of the NTC (negative thermal coefficient) decreases with increasing temperature. The NTC is the most common among the two types of Thermistors. The exponential relationship between the resistance and temperature is $R = Ae^{-kt}$

NTC

Many NTC Thermistors are made from a pressed disc, rod, plate, and bead or cast chip of a semiconductor such as a sintered metal oxide. They work because increasing the temperature of a semiconductor increases the number of active charge carrier it promotes them into the *conduction band*. The more charge carriers that are available, the more current a material can conduct. In certain materials like ferric oxide (Fe_2O_3) with titanium (Ti) doping an *n-type* semiconductor is formed and the charge carriers are electrons.

PTC

Most PTC Thermistors are of the "switching" type, which means that their resistance rises suddenly at a certain critical temperature. The devices are made of a doped polycrystalline ceramic containing barium titanate ($BaTiO_3$) and other compounds. NTC Thermistors are used as resistance thermometers in low-temperature measurements of the order of 10 K [5].

2.2.3 LM 35, LM 135, LM235 AND LM335 IC Sensors

The LM35 series are precision integrated-circuit temperature sensors, with an output voltage directly proportional to the Centigrade temperature.
LM35 has advantage over other temperature sensors as there is no need of subtracting a huge constant voltage from the output to obtain nice centigrade

scaling. There is also no need of external calibration or trimming to yield actual accuracy of 0.24 at room temperature.

The LM135, LM235 and LM335 are precision temperature sensors which can be easily calibrated. They operate as a 2-terminal Zener and the breakdown voltage is directly proportional to the absolute temperature at $10mV/^{o}K$. The circuit has a dynamic impedance of less than 1Ω and operates within a range of current from 450µA to 5mA without alteration of its characteristics. Calibrated at $+25^{o}C$, the LM135, LM235 and LM335 have a typical error of less than $1^{o}C$ over a $100^{o}C$ temperature range. Unlike other sensors, the LM135, LM235, LM335 have linear outputs [14].

2.2.4 Resistance Thermometer

Resistance thermometers, also called resistance temperature detectors (RTDs), are sensors used to measure temperature by correlating the resistance of the RTD element with temperature. Most RTD elements comprises of a length of fine coiled wire wrapped around a ceramic or glass core. The element is usually quite fragile, so it is often placed inside a sheathed probe to protect it. The RTD element is made from a pure material, typically platinum, nickel or copper. The material has a predictable change in resistance as the temperature changes; it is this predictable change that is used to determine temperature.

They are taking the place of thermocouples in many industrial applications below 600 °C, due to higher accuracy and repeatability.

Resistance thermometers are manufactured in a number of forms and offer better stability, accuracy and repeatability in many cases than thermocouples. While thermocouples use the Seebeck effect to produce a voltage, Resistance thermometers use electrical resistance and need power sources to operate.

2.3 OPTICAL TECHNIQUES

Accurate and reliable temperature measurement is a very important consideration in a number of areas of industrial and scientific activities. In many cases both contact and noncontact techniques have been applied to the measurement of temperature in a wide variety of industrial processes.

2.3.1 Pyrometer

A pyrometer is a non-contacting device that intercepts and measures thermal radiation, a process known as pyrometry. The device can be used to determine the temperature of an object's surface.

A heated object gives off electromagnetic radiation. If the object is sufficiently hot, it will give off visible light, ranging from dull red to blue-white. Even if the object is not hot enough to glow, however, it gives off infrared radiation.

How Pyrometer Works:

Two common types of pyrometers are the optical pyrometer and the radiation pyrometer. An optical pyrometer determines the temperature of a very hot object by the color of the visible light it gives off. The color of the light can be determined by comparing it with the color of an electrically heated metal wire.

A radiation pyrometer determines the temperature of an object from the radiation (infrared and, if present, visible light) given off by the object.

2.3.2 Infrared Thermometer

An infrared thermometer is a thermometer which infers temperature from a portion of the thermal radiation sometimes called blackbody radiation emitted by the object being measured. They are sometimes called laser thermometers if a laser is used to help aim the thermometer, or non-contact thermometers or temperature guns, to describe the device's ability to measure temperature from a distance. By knowing the amount of infrared energy emitted by the object and its emissivity, the object's temperature can often be determined. Infrared thermometers are a subset of devices known as "thermal radiation thermometers [6].

What Infrared Thermometers Do

Infrared thermometers work based on a phenomenon called black body radiation. Anything at a temperature above absolute zero has molecules inside of it moving around. The higher the temperature, the faster the molecules move. As they move, the molecules emit infrared radiation--a type of electromagnetic radiation below the visible spectrum of light. As they get hotter, they emit more infrared, and even start to emit visible light [7].

How Infrared Thermometer Works:

Infrared light works like visible light it can be focused, reflected or absorbed. Infrared thermometers usually use a lens to focus infrared light from one object onto a detector called a thermopile. The thermopile absorbs the infrared radiation and turns it into heat. The more infrared energy, the hotter the thermopile gets. This heat is turned into electricity. The electricity is sent to a detector, which uses it to determine the temperature of whatever the thermometer is pointed at. The more electricity, the hotter the object is.

2.4 ULTRASONIC TEMPERATURE MEASUREMENT

Ultrasonic evaluation is used for various objects and media, especially when they are opaque and thus impenetrable by electromagnetic radiation. It involves excitation of ultrasonic waves by some transducers and reception of these waves after they have passed through the whole or a part of the object under evaluation. The measured decrease in the wave's amplitude determines the ultrasound attenuation whilst the measured propagation delay specifies the ultrasound velocity. These parameters differ for various materials and also depend on the environmental conditions such as temperature.

The ultrasonic measurement of temperature is done by measuring the velocity of sound propagating in a liquid. This is done by measuring the time of flight of sound waves along the height of the channel. A well-defined relationship between the velocity of sound in a fluid and the temperature of that fluid is used to find the temperature at that instant of time.

Ultrasonic thermometers were used in the nuclear energy industry for measuring very high temperatures by placing a waveguide into a zone of interest and remotely interrogating it with ultrasonic waves. The number of the ultrasonic thermometers being used to date remains limited because of the advantages of conventional temperature sensors (thermocouples, resistance temperature detectors, Thermistors and integrated silicon temperature sensors. They were also found useful for the measurement of the temperature of hot exhaust gases in power plants.

Nevertheless, ultrasonic thermometry offers many advantages over conventional temperature sensors and is incomparable for some of its unique features. Ultrasound can be used for remote temperature measurements inside an opaque object, for example, the human body. This possibility is important for hyperthermia therapy (tightly controlled overheating of a volume of human tissue containing harmful cells) [8].

CHAPTER THREE

THERMOCOUPLE AND THERMISTORS

3.1 PRINCIPLE OF THERMOCOUPLE

A thermocouple is a temperature-measuring device consisting of two dissimilar conductors that touch each other at one or more positions. It produces a voltage when the temperature of one of the positions differs from the reference temperature at other parts of the circuit. Thermocouple is a popular used type of temperature sensor for measurement and control and can also convert a temperature gradient into electricity. One thing that differentiates thermocouples from other method of temperature measurement is that thermocouples are self-powered and require no external form of excitation. Any junction of different type of metals will produce an electric potential related to temperature. Thermocouples for practical measurement of temperature are junctions of specific alloys which have a predictable and repeatable relationship between temperature and voltage. Different alloys are used for different temperature ranges.

3.2 Type of Thermocouples

Certain combinations of alloys have become popular as industry standards. Selection of the combination is driven by cost, availability, convenience, melting point, chemical properties, stability, and output. Different types are best suited for different applications. They are usually selected on the basis of the temperature range and sensitivity required. Thermocouples with low sensitivities have correspondingly lower resolutions. Other selection criteria include the chemical inertness of the thermocouple material and whether it is magnetic or not.

Type K

Type K thermocouple consist of Alumel and chromel alloys. Alumel consist of different proportion of metals (i.e Nickel, Aluminium, Silicon and Silver) While chromel alloy consist of 90% Nickel and 10 chromium.

Type K thermocouple is the most common thermocouple. It provides the widest operating temperature range. It has a sensitivity of approximately 41μV/^{o}C. It is also cheap and many different kind of proves are available in its −200 °C to +1350 °C / -330 °F to +2460 °F range.

Type J

Type J (iron–constantan) has a smaller temperature range and a shorter lifespan at higher temperatures than the Type K (−40 °C to +750 °C). It is almost similar to type K in terms of expense and reliability. But has a higher sensitivity of about 50µV/°C.

Type E

The Type E has a stronger signal & higher accuracy than the Type K or Type J at moderate temperature ranges. The type E is also more stable than the type K, which adds to its accuracy. It contains (chromel-constantan) with a high output (68 µV/°C) which makes it well suited to cryogenic use. Also, it is non-magnetic. Wide range is −50 °C to +740 °C and Narrow range is −110 °C to +140 °C.

Type N

Type N (Nicrosil-Nisil) (nickel-chromium-silicon/nickel-silicon) thermocouples are suitable for use between −270 °C and +1300 °C owing to its stability and oxidation resistance. Sensitivity is about 39µV/°C at 900 °C, a little lower compared to type K.

3.3 Thermocouple Calibration Mathematica Program

A thermocouple is available in different combination of metals or calibrations. Each calibration has a different temperature range and environment. Although the thermocouple calibration dictates the temperature range, the maximum range is also limited by the type of the thermocouple wire.

The equipment used when calibrating thermocouple were digital thermometer, beaker, precision multimeter and thermocouple. The diagram below shows how the experiment was carried out.

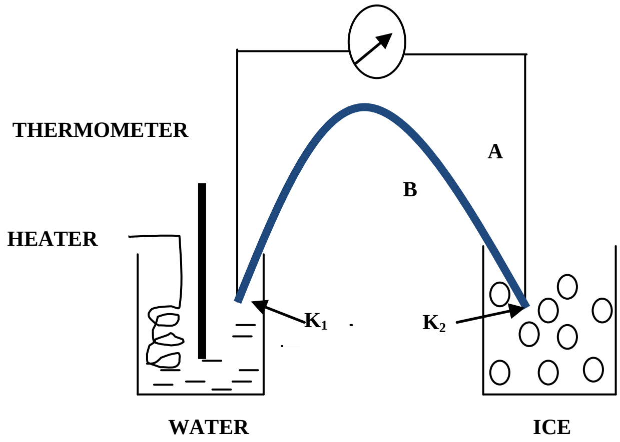

Figure 8: Thermocouple Measurement

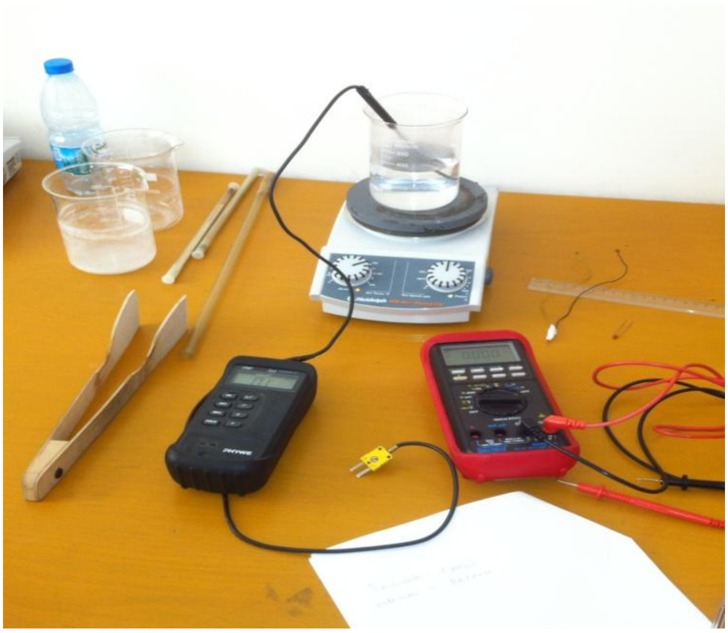

Figure 9: Thermocouple Calibration

The potential difference produce at the junction together with the corresponding temperature were recorded at regular interval as shown in the table below. The result was recorded at a room temperature of 26^{o}C.

Table 1: Temperature and Voltage Relationship of a Thermocouple

TEMPERATURE (^{o}C)	Potential Difference (mV)
30	1.25
35	1.44
40	1.64
45	1.84
50	2.04
55	2.24
60	2.44
65	2.65
70	2.87
75	3.09
80	3.32
85	3.55
90	3.80
95	4.05
100	4.32

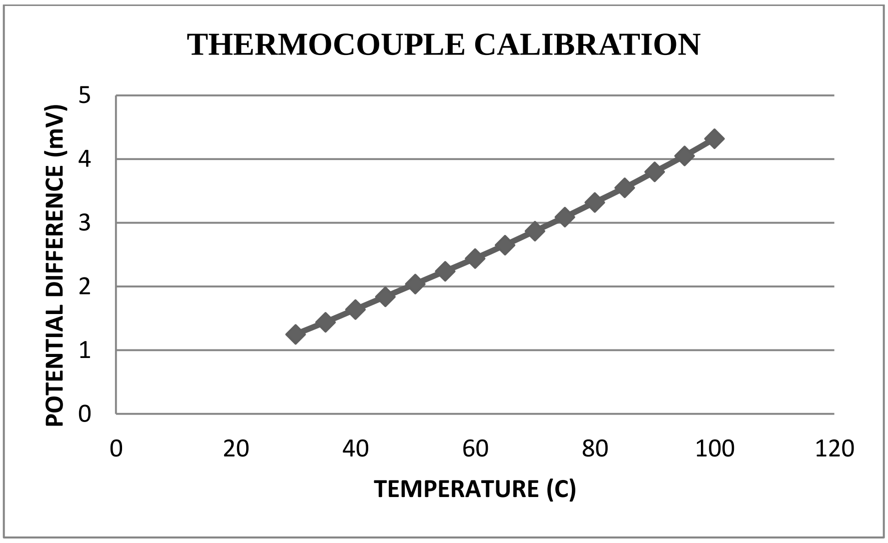

Figure 10: Graph of Potential Difference against Temperature for Thermocouple

3.3.1 Matrix Method

In this experiment a thermocouple made of alumel/chromel was calibrated by choosing three voltages at three different temperatures (i.e. 14°C, 39°C and 64°C when subtracting the room temperature of 26°C. which corresponds to 0.6mV, 1.6mV and 2.61mV potential difference).

The emf produced by the thermocouple is a cubic equation in terms of temperature. This cubic expression is then solved by a computer program written in Mathematica Programming Language.

$$V = AT^3 + BT^2 + CT \qquad \text{............................(1)}$$

Where A, B, C are constant, V is the potential difference produced at the thermocouple junction and T is the relevant temperature. Mathematica 9.0 was used to write the computer program for the calibration.

To calculate the numerical values of the constants A, B and C, temperatures T_1, T_2 and T_3 were chosen from table 1 above which corresponds to voltages V_1, V_2 and V_3.

$$V_1 = AT_1^3 + BT_1^2 + CT_1 \quad \text{..............................(2)}$$

$$V_2 = AT_2^3 + BT_2^2 + CT_2 \quad \text{..............................(3)}$$

$$V_3 = AT_3^3 + BT_3^2 + CT_3 \quad \text{..............................(4)}$$

The three equations with three unknowns above can then be solved. This is the best way to take advantage of determinants.

$$D_o = \begin{pmatrix} T_1^3 & T_1^2 & T_1 \\ T_2^3 & T_2^2 & T_2 \\ T_3^3 & T_3^2 & T_3 \end{pmatrix}$$

$$D_1 = \begin{pmatrix} V_1 & T_1^2 & T_1 \\ V_2 & T_2^2 & T_2 \\ V_3 & T_3^2 & T_3 \end{pmatrix}$$

$$D_2 = \begin{pmatrix} T_1^3 & V_1 & T_1 \\ T_2^3 & V_2 & T_2 \\ T_3^3 & V_3 & T_3 \end{pmatrix}$$

$$D_3 = \begin{pmatrix} T_1^3 & T_1^2 & V_1 \\ T_2^3 & T_2^2 & V_2 \\ T_3^3 & T_3^2 & V_3 \end{pmatrix}$$

$$\mathrm{DetD}_0 = T_1T_2(T_2 - T_3)T_3(T_1^2 - T_1T_2 - T_1T_3 + T_2T_3)$$

$$\mathrm{DetD}_1 = -T_2^2T_3V_1 + T_2T_3^2V_1 + T_1^2T_3V_2 - T_1T_3^2V_2 - T_1^2T_2V_3 + T_1T_2^2V_3$$

$$\mathrm{DetD}_2 = T_2^3T_3V_1 - T_2T_3^3V_1 - T_1^3T_3V_2 + T_1T_3^3V_2 + T_1^3T_2V_3 - T_1T_2^3V_3$$

$$\mathrm{DetD}_3 = -T_2^3T_3^2V_1 + T_2^2T_3^3V_1 + T_1^3T_3^2V_2 - T_1^2T_3^3V_2 - T_1^3T_2^2V_3 + T_1^2T_2^3V_3$$

The three unknown A, B and C can then be calculated using the formula

$$A = \frac{-\mathrm{DetD}_1}{\mathrm{DetD}_0}, \mathrm{B} = \frac{-\mathrm{DetD}_2}{\mathrm{DetD}_0}, \mathrm{C} = \frac{-\mathrm{DetD}_3}{\mathrm{DetD}_0}$$

$$A = 1.26969 \times 10^{-6}, B = -0.000140554, C = 0.044576$$

The values of A, B and C can then be substituted in equation (1).

3.3.2 Curve Fitting

Mathematica is a system for doing mathematics on the computer. It can do numeric, symbolic, graphics and is also a programming language. Mathematica has infinite precision. It can plot functions of a single variable; make contour, surface and density plots with special shading and lighting effects.

There are many situations where one wants to find a formula that best fits a given set of data. One way to do this in *Mathematica* is to use *Fit*.

Fit takes a list of functions, and uses a definite and efficient procedure to find what linear combination of these functions gives the best least-squares fit to your data. Sometimes, however, you may want to find a *nonlinear fit* that does not just consist of a linear combination of specified functions. You can do this using *FindFit*, which takes a function of any form, and then search for values of parameters that yield the best fit to your data.

$$\mathrm{fp} = \mathrm{List}[\{0{,}0\},\{14{,}0.6\},\{39{,}1.6\},\{64{,}2.61\}]$$

$$\mathrm{Equ} = \mathrm{Fit}[\mathrm{fp},\{t\char`^3, t\char`^2, t\}, t]$$

3.4 LM 35 CALIBRATIONS

The LM35 series are precision integrated-circuit temperature sensors, whose output voltage is linearly proportional to the Celsius (Centigrade) temperature. The LM35 thus has an advantage over linear temperature sensors calibrated in Kelvin, as the user is not required to subtract a large constant voltage from its output to obtain convenient Centigrade scaling. The LM35 does not require any external calibration or trimming to provide typical accuracies over certain range of temperature.

The data I got from the experiment I carried out in calibrating the LM35 is shown below,

Table 2: Temperature and Voltage Relationship of LM35 Temperature Sensors

TEMPERATURE (^{o}C)	VOLTAGE (mV)
22	225
24	240
26	260
28	280
30	301
32	321
34	341
36	363
38	380
40	389
42	416
44	430
46	448
48	466
50	486
52	510

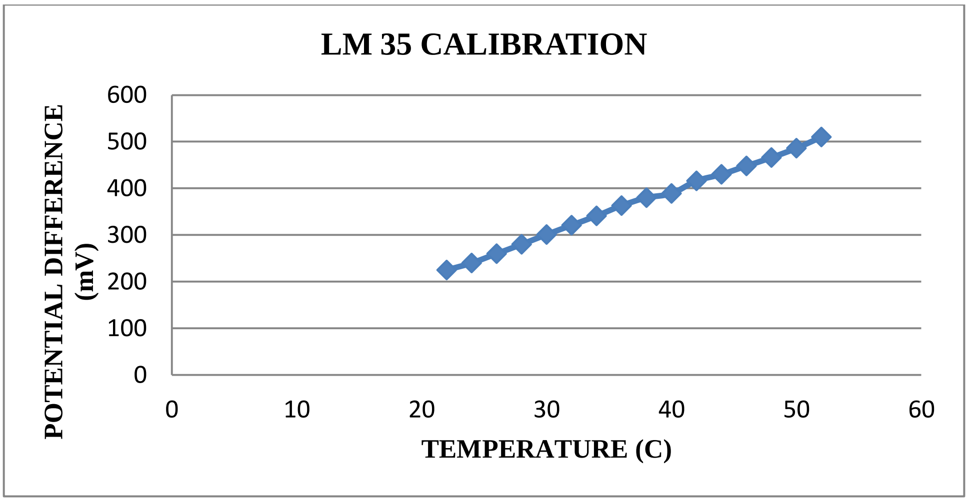

Figure 11: Graph of Potential Difference against Temperature for LM35

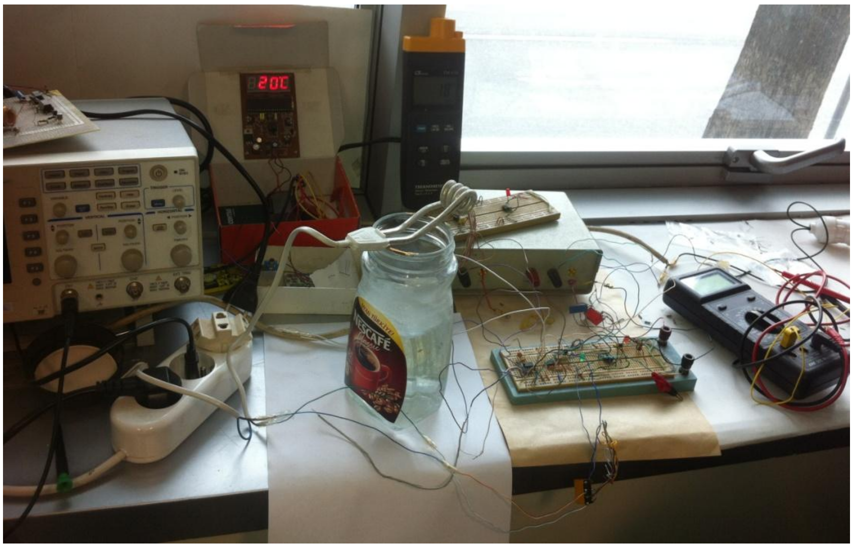

Figure 12: The Photograph of LM 35 Calibrations Circuit

3.5 THERMISTOR MEASUREMENT

In this measurement NTC (Negative Temperature Coefficient) thermistor was used. NTC Thermistors are thermally sensitive resistors made from a mixture of Mn, Ni, Co, Cu, Fe oxides. This semi-conducting material behaves as an NTC resistor, whose resistance decreases with increasing temperature. This Negative Temperature Coefficient effect can result from an external change of the ambient temperature or an internal heating due to the Joule effect of a current flowing through the thermistor.

The data I got from the experiment I carried out in calibrating the Thermistor is shown below

Table 3: Temperature and Resistance Relationship of a Thermistor

TEMPRATURE (^{O}C)	RESISTANCE (Ω)
24	940
26	870
28	820
30	770
32	712
34	670
36	623
38	571
40	540
42	480
44	470
46	431
48	410
50	380
52	350
54	331

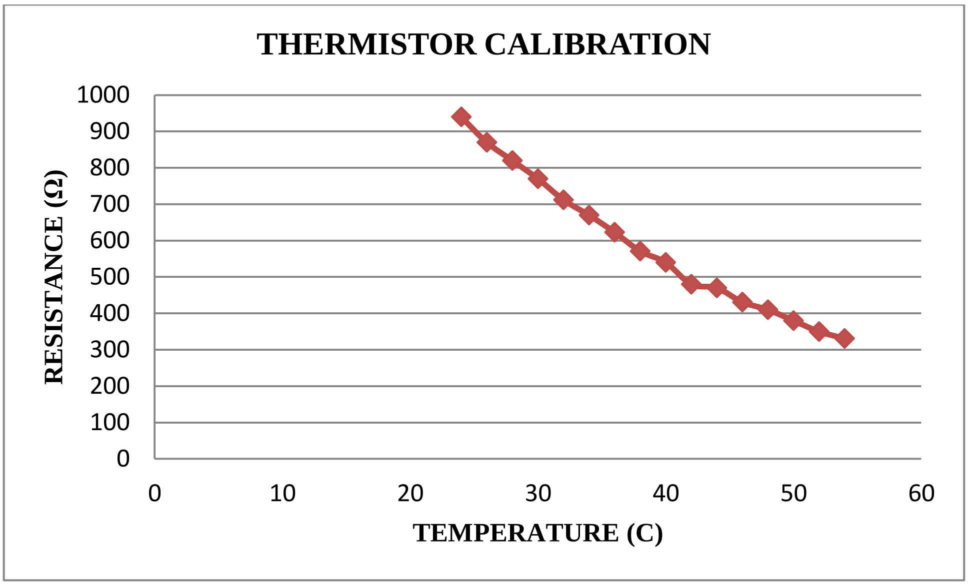

Figure 13: Graph of Potential Difference against Temperature for Thermistor

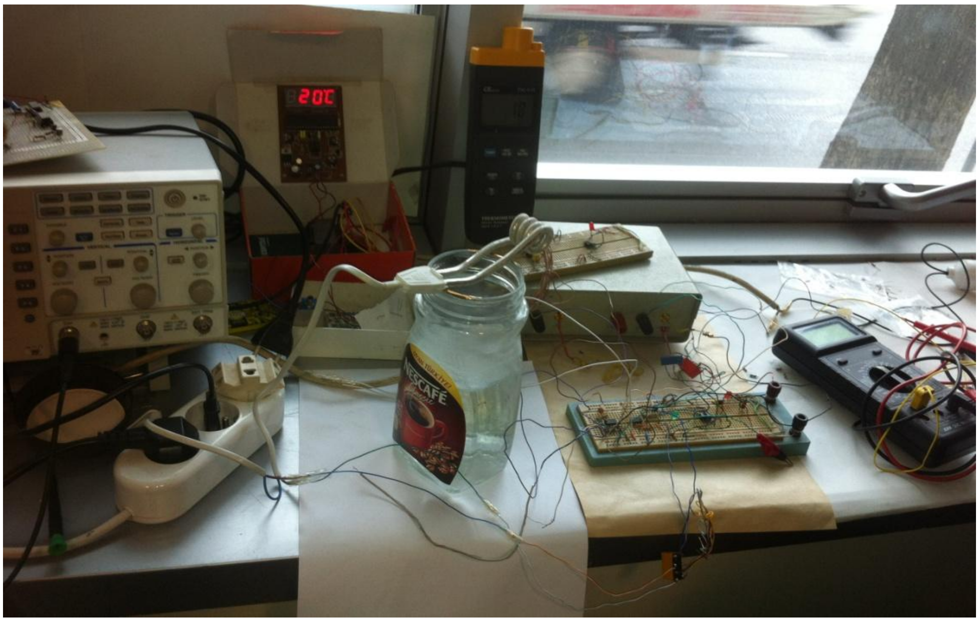

Figure 14: Photograph of the Constructed Circuit for the Calibration of Thermocouple, Thermistor and LM35

CHAPTER FOUR

CONTROL CIRCUIT

4.1 OPERATIONAL AMPLIFIER AND DIFFERENTIAL AMPLIFIERS

Two amplifies were used in the circuit. The operational amplifier, that is LM308, serves to amplifier the small signal coming from the thermocouple. The other amplifier LM358 was used as a comparator that compares the signal coming from the first amplifier with the fixed reference voltage.

4.1.1 LM308

The operational amplifier used in the circuit is LM308. LM308 is a precision operational amplifier with much higher advantage over FET amplifiers, especially in terms of operating temperature range. LM308 has very low offset voltage and low input current. This gives it higher advantage to wipeout offset adjustment in many scenarios.

In the circuit a dual power supply was used to power the LM308 with +12V at pin 7 and -12V at pin 4. The signal coming from thermocouple were connected to pin 2 and 3 of the op-amp and pin 6 serve as the output of the op amp as shown in the diagram below.

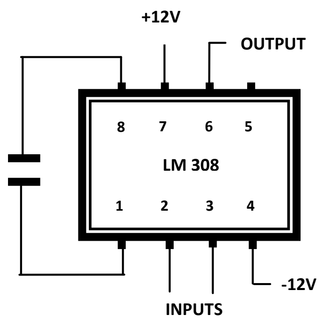

Figure 15: Pin Configuration of LM308 Op-amp

This op-amp (LM308) served as an amplifier and it multiply the voltage coming from the thermocouple. Since the signal coming from the thermocouple is in the fraction of millivolts for every degree rise in temperature. This means that the value is too small to be fed directly to the comparator. The output value is then fed to another amplifier, in this case a comparator. The comparator then compares the amplified voltage with the reference voltage, and gives its output according to the comparative result. Appropriate resistors were used to provide the required amplification.

A capacitor was connected between pin 1 and 8 in order to improve the rejection of power supply noise by about a factor of 10, also to normalize the slew rate of the amplified output.

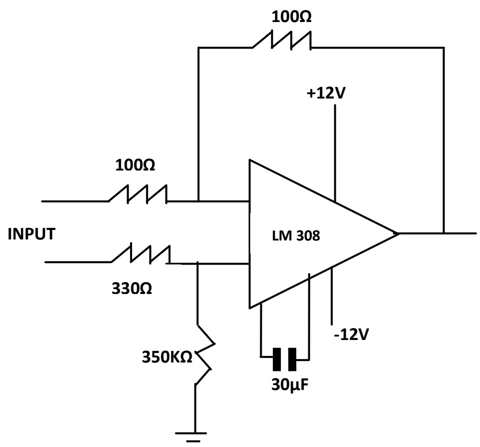

Figure 16: LM308 Amplification Circuit

4.1.2 LM358

The comparator used in the circuit, LM358. LM358 consist of two independent high gain internally frequency compensated operational amplifier. LM358 made purposely to work from a single power supply over a wide range of voltages.

LM358 in this circuit has two inputs, the fixed reference voltage at pin 3 and the variable voltage coming from the first amplifier at pin 2. With the appropriate resistors connected it gives an output of either 5V or 0V.

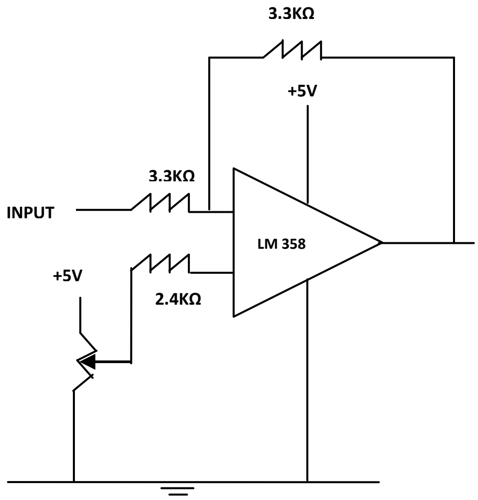

Figure 17: LM358 Comparator Circuit

4.2 RELAY AND TRANSISTOR

4.2.1 Relay

A relay is a simple electromechanical switch made up of an electromagnet and a set of contacts. Relay allows a small current flow circuit to control a higher current circuit.

The relay used in the circuit is 5V PCB relay JRC-19F, 4078, which has 8 pins.

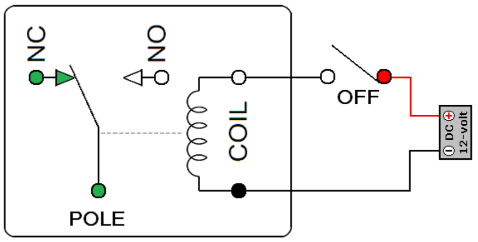

Figure 18: 12V DC relay

4.2.2 Transistor

A transistor is a semiconductor device used to amplify and switch electronic signals and electrical power. It is composed of semiconductor material with at least three terminals for connection to an external circuit.

The transistor used in this circuit is MPS2222A (BC 337, npn) it has very fast switching

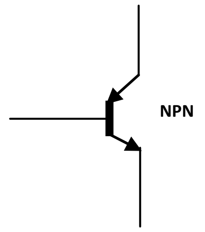

Figure 19: Transistor Symbol

4.3THERMOCOUPLE CONTROL CIRCUIT

The technique involved in the controlling process comprises the use of electronic temperature sensors, such as thermocouple thermistor and LM35.with the appropriate switching circuit the device can be used to control other equipments, such as Air condition, Refrigerator e.t.c. The figure below shows how the complete circuit looks like

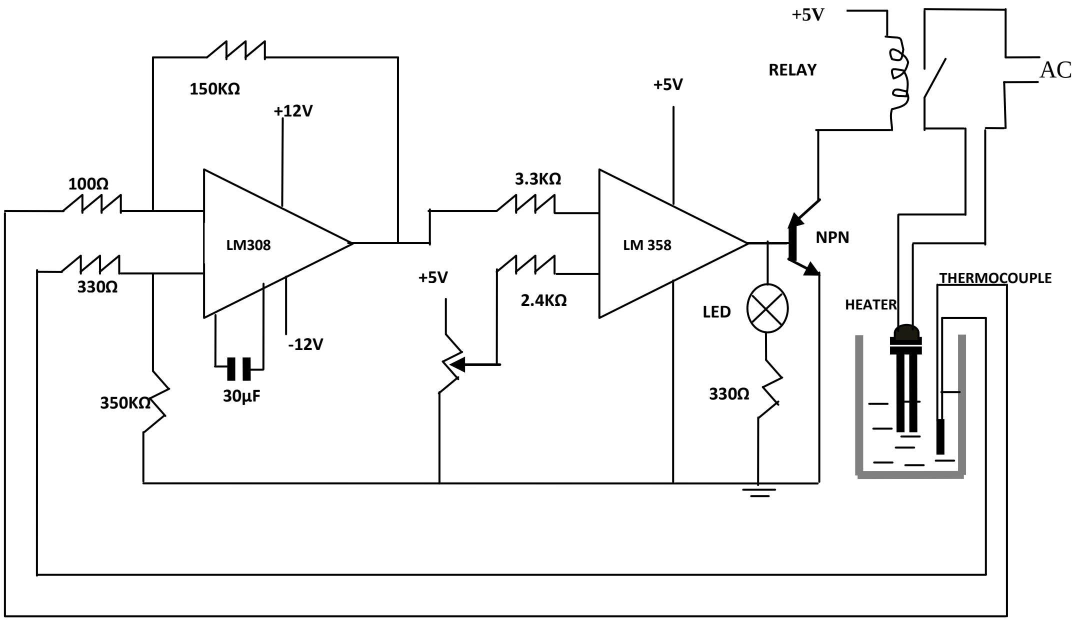

Figure 20: Thermocouple Based Control Circuit

4.4 HEATING AND CONTROL

The technique involved in the controlling process comprises the use of electronic temperature sensors, such as thermocouple thermistor and LM35.with the appropriate switching circuit the device can be used to control other equipment, such as Air condition, Refrigerator e.t.c. The figure below shows how the complete circuit looks like.

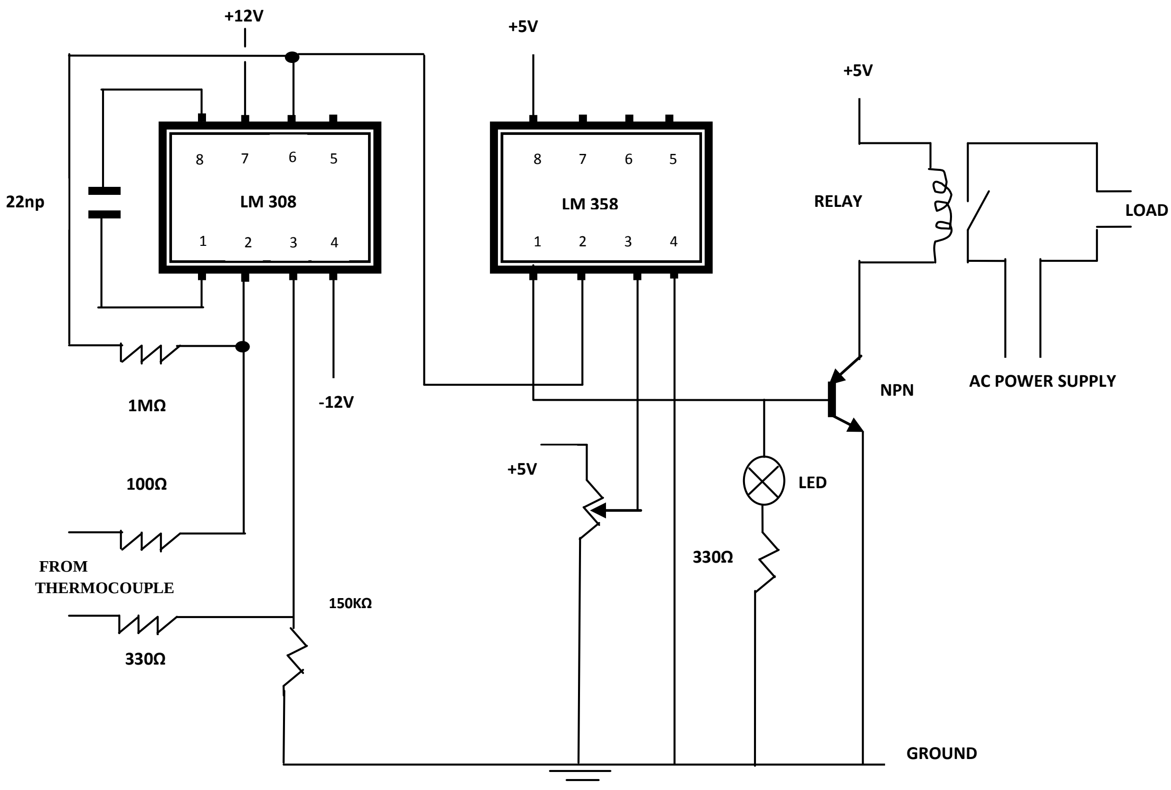

Figure 21: Thermocouple Control Circuit

4.5. MEASUREMENT AND CONTROL USING THERMISTOR

Thermistor is a type of resistor whose resistance varies significantly with temperature. Thermistors are inexpensive, easy to use and easily obtainable temperature sensor.

The circuit below shows how a thermistor can be used as a temperature sensor.

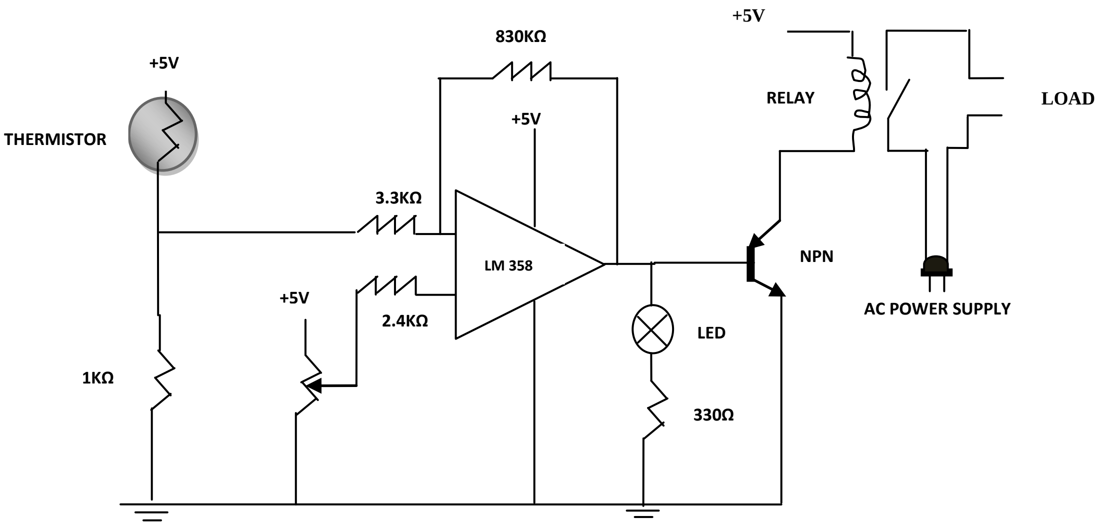

Figure 22: Circuit Diagram of a Temperature Control Using Thermistor

4.6 LM135, LM235 AND LM335 CIRCUITS

The LM35 series are precision integrated-circuit temperature sensors, with an output voltage directly proportional to the Centigrade temperature.

LM35 series has advantage over other temperature sensors as there is no need to subtract a huge constant voltage from the output to obtain nice centigrade scaling. There is also no need to of external calibration or trimming to yield actual accuracy of 0.24 at room temperature.

The circuit diagram used to control temperature using LM35 series is shown in the figure below,

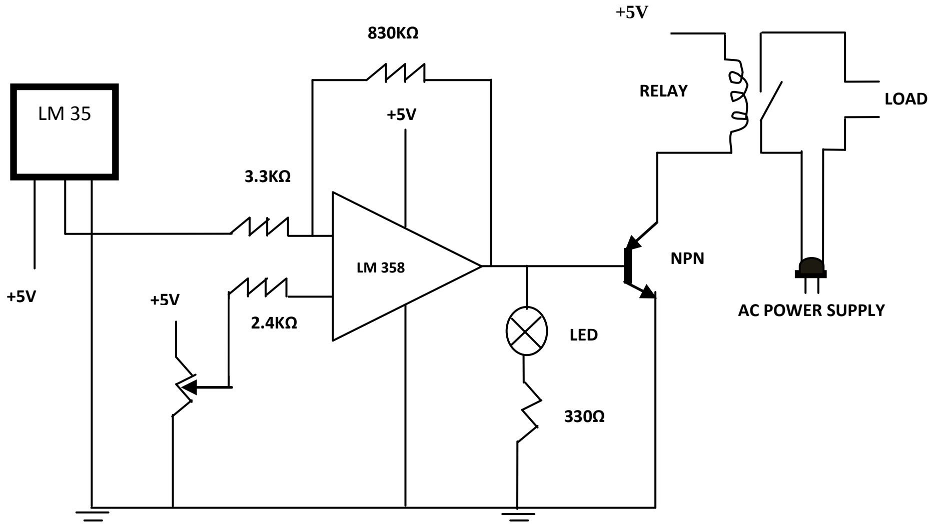

Figure 23: Circuit Diagram of a Temperature Control Using LM35

4.7 THERMOCOUPLE CALIBRATION

A thermocouple consists of two dissimilar conductors joined to form a circuit. First discover that a thermocouple would produce a current in a closed circuit when one junction is at a different temperature from the other.

The calibration was made using simple laboratory apparatus as shown in the diagram below, such as beaker, precision multimeter, Thermometer and thermocouple. The emf of the thermocouple was recorded using multimeter; while the corresponding temperature change was recorded using digital thermometer.

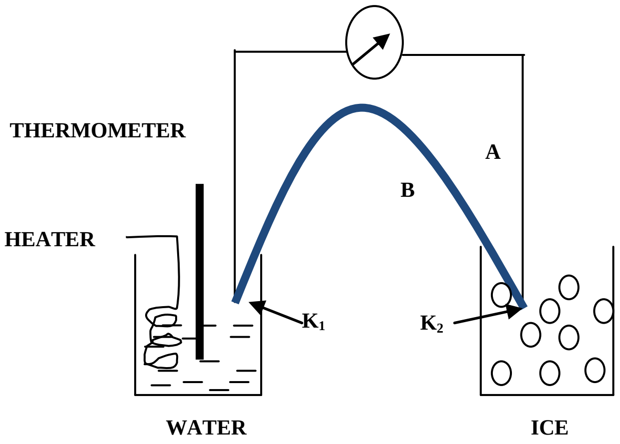

Figure 24: Thermocouple Measurement

4.7.1 Matrix Method

In this experiment a thermocouple made of Alumel chromel was calibrated by choosing three voltages at three different temperatures (i.e. 14°C, 39°C and 64°C which corresponds to 0.6mV, 1.6mV and 2.61mV potential difference).

The emf produce by the thermocouple is a cubic equation in terms of temperature as shown in Chapter three (i.e. equation 1). This cubic expression is then solved by a computer program written in Mathematica Programming Language.

Where A, B, C are constant, V is the potential difference produce at the thermocouple junction and T is the relevant temperature. Mathematica 9.0 was used to write the computer program for the calibration.

To calculate the numerical values of the constant A, B and C, temperatures T_1, T_2 and T_3 were chosen from table 1 above which corresponds to voltages V_1, V_2 and V_3.

The three equations (i.e. equations 2, 3 and 4) with three unknown can then be solved. This is the best way to take advantage of determinants. Determinants $DetD_0$, $DetD_1$, $DetD_2$and $DetD_3$ were evaluated as shown in Chapter three. The numerical values of A, B and C were calculated as follows:

$$A = \frac{-\mathrm{DetD}_1}{\mathrm{DetD}_0},\ \mathrm{B} = \frac{-\mathrm{DetD}_2}{\mathrm{DetD}_0},\ \mathrm{C} = \frac{-\mathrm{DetD}_3}{\mathrm{DetD}_0}$$

$$A = 1.26969 \times 10^{-6}, B = -0.000140554, C = 0.044576$$

The values of A, B and C can then be substituted in equation (1)

4.7.2 Curve Fitting

Mathematica is a system for doing mathematics on the computer. It can do numeric, symbolic, graphics and is also a programming language. Mathematica has infinite precision. It can plot functions of a single variable; make contour, surface and density plots with special shading and lighting effects.

There are many situations where one wants to find a formula that best fits a given set of data. One way to do this in *Mathematica* is to use *Fit*.

Fit takes a list of functions, and uses a definite and efficient procedure to find what linear combination of these functions gives the best least-squares fit to your data. Sometimes, however, you may want to find a *nonlinear fit* that does not just consist of a linear combination of specified functions. You can do this using, *FindFit* which takes a function of any form, and then searches for values of parameters that yield the best fit to your data.

The emf of a thermocouple is a cubic equation in terms of temperature. This cubic equation is solved by a computer program written in Mathematica or other high level computer language

The cubic equation is

$$V = AT^3 + BT^2 + CT$$

$$\mathrm{fp} = \mathrm{List}[\{0,0\},\{14,0.6\},\{39,1.6\},\{64,2.61\}]$$

$$\mathrm{Equ} = \mathrm{Fit}[\mathrm{fp},\{t\text{^}3, t\text{^}2, t\}, t]$$

Given the corresponding values of temperature and the potential difference as $[\{0,0\},\{14,0.6\},\{39,1.6\},\{64,2.61\}]$ Mathematica is able to generate the cubic equation as show

$$0.044576t - 0.0001.40554t^2 + 1.26969 \times 10^{-6}t^3$$

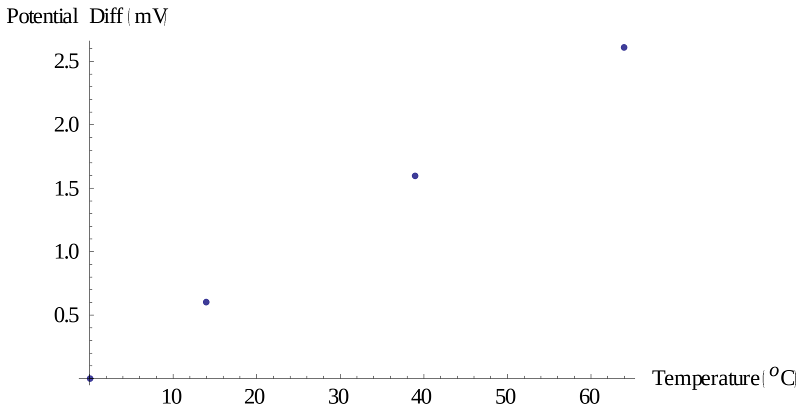

Figure 25: Graph Plot by Mathematica of Temperature and Potential Difference Relationship for Themocouple

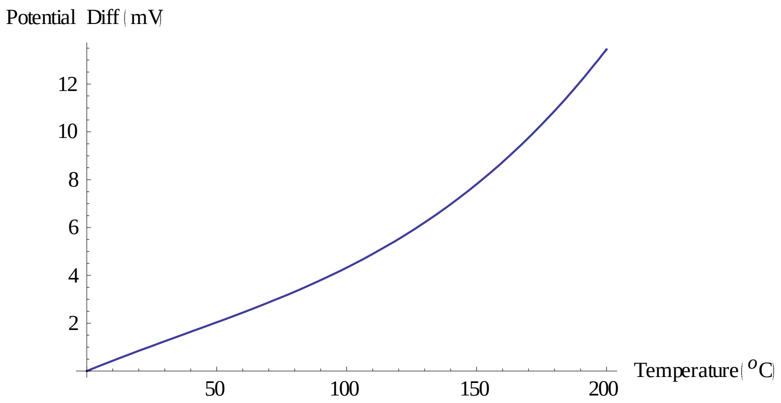

Figure 26: Graph Plot by Mathematica of Temperature and Potential Difference Relationship for Themocouple

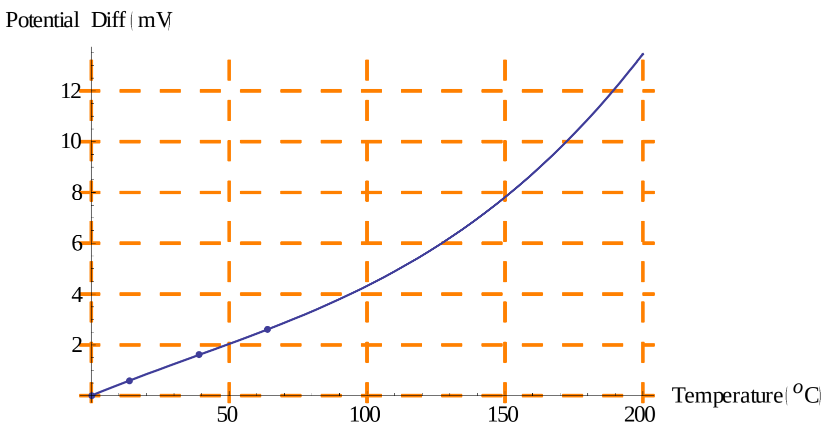

Figure 27: Graph Plot by Mathematica of Temperature and Potential Difference Relationship for Thermocouple

CHAPTER FIVE

5.1 SUMMARY

Temperature monitoring is becoming more and more important in a lot of industries, like Food industry, the laboratory and pharmaceutical industry or even in environmental monitoring, temperature control is vital. Therefore different methods of temperature measurement recording and control are very important.

In this research project different temperature measuring techniques were examined. A circuit was build that can be used as temperature control system. Also a computer program known as Mathematica was used in calibrating the thermocouple. In the case of thermocouples the potential difference produced at the two ends happens to be so small that additional hardware component is required to rise it up. Amplification circuit was produced to amplifier the small voltage produced by the thermocouple to the level that the second amplifier (i.e. LM358) can recognize it. LM358 op amp was used as a comparator to compare the amplified signal against the reference voltage. Then a transistor was also used, which serves to switch other equipments ON and OFF or toggle a relay. A thermocouple made of copper and constantan (alloy) thin wire was calibrated by measuring three voltages at three different temperatures. The emf on a thermocouple is a cubic equation in terms of temperature. This cubic expression is then solved by a computer program written in Mathematica.

5.2 CONCLUSION

The circuit to measure temperature using different approaches was constructed. It involves the use of electronic components like Amplifies, Transistors and Relays. Two amplifies were used in the circuit. The operational amplifier that is LM308 serves to amplifier the small signal coming from the thermocouple. The other amplifier LM358 was used as a comparator that compares the signal coming from the first amplifier with the fixed reference voltage.

The signal that comes from the thermocouple was connected to an amplifier. Since the signal coming from the thermocouple is in the fraction of millivolts for every degree rise in temperature. This means that the value is too small to fed directly to a comparator. Therefore it needs to be amplified.

Mathematica programming language was used to write the program for the calibration of the thermocouple. The program tested successfully. In the experiment a thermocouple made of Alumel chromel was calibrated by choosing three voltages at three different temperatures (i.e. 14^{o}C, 39^{o}C and 64^{o}C which corresponds to 0.6mV, 1.6mV and 2.61mV potential difference). The emf produce by the thermocouple is a cubic equation in terms of temperature. This cubic expression is then solved by a computer program written in Mathematica Programming Language. This shows that temperature can be measured using different approaches from a single circuit.

5.3 SUGGESTIONS

The result obtained from this research highlights the importance of temperature measurement. The result also shows that simple and inexpensive electronic circuits can be made to measure and control temperature. Two simple amplifies, LM308 and LM358 were used to create a circuit that measures temperature, and used the result of the measurement to control other equipment such as refrigerator and Air Condition.

In order to produce and create efficient ways of measuring temperature, more resources should be poured into research and development, despite enormous advantage of temperature measurement in areas such as Medicine, Pharmaceutical and Manufacturing Industries, indications have shown that there is still shortage of professionals in the field of temperature measurement.

5.4 APPENDICES

APPENDIX: 1 MATHEMATICA PROGRAM (THERMOCOUPLE CALIBRATION USING DETERMINANT METHOD)

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Style[" The Aim of this program is to use a computer program to create calibration of Thermocouple use in temperature control systems. The emf on a thermocouple is a cubic equation in terms of temperature.This cubic expression is solved by a computer program written in Mathematica or other high level computer language The cubic equation is given as",16,Bold,Blue]
Text[Style[Style["$V=AT^3+BT^2+CT$",16,Bold,Black],TextAlignment→Center]]
Style["Where A,B & C are constants,V is the potential difference between the ends (emf),and T is the relevant temperature.",15, Blue,Bold]

Print["V_1=A*T_1^3+B*T_1^2+C*T_1"];Print["V_2=A*T_2^3+B*T_2]^2+C*T_2"];Print["V_3=A*T_3^3+B*T_3^2+C*T_3"]

Style["These three equations,three unknown A,B,C can be found.This is the best way to take advantage of determinantlardan",15,Blue,Bold]

D_0=MatrixForm[{{"T_1^3,T_1^2,T_1"},{"T_2^3, T_2^2,T_2"},{"T_3^3,T,$_3^2$,T_3"}}];
D_1=MatrixForm[{{"V_1,T,$_1^2$,T_1"},{"V_2,T,$_2^2$,T_2"},{"V_3,T,$_3^2$,T_3"}}];
D_2=MatrixForm[{{"T,$_1^3$,V_1,T_1"},{"T,$_2^3$,V_2,T_2"},{"T,$_3^3$,V_3,T_3"}

```
}];
D_3=MatrixForm[{{"T,_1^3,T,_1^2,V_1"},{"T,_2^3,T,_2]^2,V_2"},{"T,_3]^3,T
,3]^2,V_3"}}];
Print["D_0=",D_0];Print["D_1=",D_1];Print["D_2=",D_2];Print["
D_3=",D_3];

Print["DetD_0=T_1 T_2 (T_2-T_3) T_3 (T_1^2-T_1 T_2-T_1 T_3+T_2 T_3)"];
Print["DetD_1=-T_2^2 T_3 V_1+T_2 T_3^2 V_1+T_1^2 T_3 V_2-T_1 T_3^2 V_2-T_1^2 T_2
V_3+T_1 T_2^2 V_3"];
Print["DetD_2=T_2^3 T_3 V_1-T_2 T_3^3 V_1-T_1^3 T_3 V_2+T_1 T_3^3 V_2+T_1^3 T_2 V_3-T_1
T_2^3 V_3"];
Print["DetD_3=-T_2^3 T_3^2 V_1+T_2^2 T_3^3 V_1+T_1^3 T_3^2 V_2-T_1^2 T_3^3 V_2-T_1^3 T_2^2 V_3+
T_1^2 T_2^3 V_3"];
DetD_0=T_1 T_2 (T_2-T_3) T_3 (T_1^2· T_1 T_2· T_1 T_3· T_2 T_3);
DetD_1=-T_2^2 T_3 V_1+T_2 T_3^2 V_1+T_1^2 T_3 V_2-T_1 T_3^2 V_2-T_1^2 T_2 V_3+T_1 T_2^2 V_3;
DetD_2=T_2^3 T_3 V_1-T_2 T_3^3 V_1-T_1^3 T_3 V_2+T_1 T_3^3 V_2+T_1^3 T_2 V_3-T_1 T_2^3 V_3;
DetD_3=-T_2^3 T_3^2 V_1+T_2^2 T_3^3 V_1+T_1^3 T_3^2 V_2-T_1^2 T_3^3 V_2-T_1^3 T_2^2 V_3+T_1^2 T_2^3 V_3;
T_1=14 ; T_2=39; T_3=64;
V_1=0.6; V_2=1.6;V_3=2.61;
Style["The values of A,B&C(H) from the above
equations are",15,Blue,Bold]
Print["A=-DetD_1/DetD_0"];Print["B=-
DetD_2/DetD_0"];Print["H=-DetD_3/DetD_0"];
A=-DetD_1/DetD_0; B=-DetD_2/DetD_0; H=-DetD_3/DetD_0;
Print["A=",A];Print["B=",B];Print["C=",H];
Do[ R[t]=A* t^3+B*t^2+H*t,{t,0,300,1} ]
Print["Temperature ","      Emf(mV)"]
Print["----------------------"]
Do[Print[t ,"                 ",NumberForm[R[t],{9,7}]]
,{t,0,200,5}]
W[t_] =A* t^3+B*t^2+H*t;
Plot[W[t],{t,0,60},AxesLabel→{"Temperature(°C)","Pot
ential
Diff(mV)"},GridLines→Automatic,GridLinesStyle→Direct
ive[Orange,Dashed]]
```

APPENDIX: 2 MATHEMATICA PROGRAM (THERMOCOUPLE CALIBRATION USING CURVE FITTING)

```
Style["DATE:SEPTEMBER,2013",16,Bold,Black]
Style["TEMPERATURE MEASUREMENT AND CONTROL SYSTEM",22,Bold,Black]
Style["THERMOCOUPLE CALIBRATION",20,Bold,Black]
Style[" The Aim of this program is to use a computer program to create calibration of Thermocouple use in temperature control systems. The emf on a thermocouple is a cubic equation in terms of temperature.This cubic expression is solved by a computer program written in Mathematica or other high level computer language The cubic equation is given as",16,Bold,Blue]

Text[Style[Style["V=AT^3+BT^2+CT",16,Bold,Black],Text Alignment▮Center]]
Style["1. USING CURVE FITTING",20,Bold,Black]

fp=List[{0,0},{14,0.6},{39,1.6},{64,2.61}]
Equ=Fit[fp,{t^3,t^2,t},t]
gp=ListPlot[fp,AxesLabel▮{"Temperature(°C)","Potential Diff(mV)"}]
Plot
[Equ,{t,0,200},AxesLabel▮{"Temperature(°C)","Potential Diff(mV)"}]
Show[%,gp,Prolog▮AbsolutePointSize[4],
GridLines▮Automatic,GridLinesStyle▮Directive[Orange,Dashed],  AxesLabel▮{"Temperature(°C)","Potential Diff(mV)"}]
```

APPENDIX 3: LM 308 SPECIFICATION SHEET

LM308A ABSOLUTE MAXIMUM RATINGS

Supply Voltage	±18V
Power dissipation	500mW
Differential Input Current	±10mV
Input Voltage	±15V
Output Short-Circuit Duration	Continuous
Operating Temperature Range	0^{o}C t0 70^{o}C
Storage Tempera Range	-65^{o}C to $+150^{o}$C
H-Package Lead Temperature (Soldering, 10 sec)	300^{o}C
Lead Temperature (Soldering, 10sec)	260^{o}C

ELECTRICAL CHARACTERISTICS

Parameter	Condition	Min	Typ	Max	Units
Input Offset Voltage	T_A=25^{o}C		0.3	0.5	mV
Input Offset Current	T_A=25^{o}C		0.2	1	nA
Input Bias Current	T_A=25^{o}C		1.5	7	nA
Input Resistance	T_A=25^{o}C	10	40		MΩ
Supply Current	T_A=25^{o}C, V_S= ±15V		0.3	0.8	mA
Large Signal Voltage Gain	T_A=25^{o}C V_S =±15V	80	300		V/mV
Input Offset Current				1.5	nA
Input Biase Current				10	nA
Output Voltage Swing	V_S=±15V, R_L=10kΩ	±13	±14		V
Input Voltage Range	V_S=±15V	±14			V
Common Mode Rejection Ratio		96	110		dB
Supply Voltage rejection Ratio		96	110		dB

APPENDIX 4: LM 358 SPECIFICATION SHEET

ABSOLUTE MAXIMUM RATINGS

	LM358
Supply Voltage	32V
Differential Input Voltage	32V
Input Voltage	-0.3V to +32V
Power Dissipation	
PDIP (P)	830mW
TO-99 (LMC)	550mW
SOIC (D)	530mW
Operating Temperature Range	0^oC to 70^oC
Storage Temperature Range	-65^oC to $+150^oC$

ELECTRICAL CHARACTERISTICS

V^+ = +5V, unless otherwise stated

Parameter	Condition	LM358		
		Min	Typ	Max
Input offset Voltage	$T_A = 25^oC$		2	2
Input Bias Current	$I_{IN(+)}$ or $I_{IN(-)}$, $T_A = 25^oC$		45	100
Input Offset Current	$I_{IN}(+)$ - $I_{IN}(-)$, VCM = 0V, T_A = 25°C		5	30
Input Common-Mode	V+ = 30V	0		V^+ -1.5
Voltage Range	LM2904, V+ = 26V), TA = 25°C			
Supply Current	Over Full Temperature Range			
	RL = ∞ on All Op Amps			
	V+ = 30V (LM2904 V+ = 26V)		1	2
	V+ = 5V		0.5	1.2

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